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Abstract. Four experiments using a lexical decision task showed systematic effects of the anagram relationship between lexical units as well as between prime and target stimuli, even though the letter strings had no common letters in the same position. An "anagram frequency effect", similar to the well known "neighborhood frequency effect", was observed in Experiment 1. An anagram priming effect was observed in Experiment 4. An anagram prime x lexical anagram interaction effect was observed in Experiments 2 and 3. We concluded that the mental lexicon is activated by position-free letter codes, together with other units that separately encode the order information.

What exactly is the "orthographic similarity" of words, or letter strings, for human readers? The answer to this question is essential for modeling word recognition processes, as well as for methodological purpose. The hypothesis that some kind of holistic process contributes to word recognition received some supporting evidence (Allen & Emerson, 1991; Lété & Pynte, 2003), however, there is also a large amount of empirical evidence that analytical processes play an essential role (McClelland, 1976). As a consequence, most current models of word recognition postulate that the access to the mental lexicon is mediated by the recognition of component orthographic units such as letters. Given that a word is an ordered sequence of letters, and that human readers can discriminate anagrams, one must of course assume that some perceptual mechanism takes into account letter order information. There are a priori various possible ways of doing this, leading to very different word recognition models. The Interactive Activation Model (McClelland & Rumelhart, 1981), as well as the Activation-Verification Model (Paap, Newsome, McDonald, & Schvaneveldt, 1982), assumes that the letters are extracted from the visual stimulus by independent and position specific processing channels working in parallel. As a result, the letter codes are also position specific, with the consequence that the word MEAN = {(M, 1), (E, 2), (A, 3), (N, 4)} and its anagram NAME = {(N, 1), (A, 2), (M, 3), (E, 4)}, for example, have no common elements. A major difficulty with this type of approach is that it requires that a visual pre-processing be able to segment the stimulus into portions of image corresponding to the component letters to be recognized, before assigning each portion to the appropriate processing channel. This is possible only if there are topological or geometrical criteria that allow for suitable segmentation of the stimulus. This is the case if one considers only printed words where letters are not connected. However, human readers can also read strings of connected characters (cursive handwriting, Arabic writing, etc.), and in this case, one can hardly hope to find a suitable segmentation pre-process (see Manso De Zuniga, Humphreys, & Evett, 1991; Srihari & Bozinovic, 1987). It seems that the problem of connected characters can be effectively solved using another family of neuron-like models, namely the so-called "Neocognitrons" (Fukushima, 1992; Fukushima & Imagawa, 1993; Fukushima, Miyake, & Ito, 1983). In recent versions of this model, a moving attentional window is involved in the successive extraction of different letters from the stimulus image. The letter codes thus made available are position-free, and the position of each extracted letter can only be known by taking into account the visual location of the attentional window at the time where the letter was extracted. Hence, the identity and the position of letters are clearly dissociated in this type of model. The Neocognitrons exhibited some qualitatively interesting performance in the perceptual analysis of printed as well as handwritten materials. However, the serial recognition of letters leads to unrealistic predictions in terms of processing time, although there are some empirical supporting arguments for the hypothesis of a serial component in the perceptual analysis of words (Courrieu, 1986; Courrieu & Dô, 1987). Another possibility is that the letters are extracted together with their local context, in the form of a set of small overlapping multi-letter units such as bigrams or trigrams (Seidenberg & McClelland, 1989). For example, MEAN = {(_ME), (MEA), (EAN), (AN_)}, where '_' stands for the space character, is a possible representation using trigrams. However, one must take care that the size of an alphabet of trigrams is in the order of $27^3 = 19683$, and even if one removes impossible trigrams, this is not an economical code. The size of an alphabet of bigrams is in the order of $27^2 = 729$, which seems more reasonable and compatible with the number of input connections of biological neurons. One can also imagine that only certain particularly relevant trigrams are encoded together with bigrams. It is obvious that one can develop many variants of the above models in order to improve their performance or to account for particular empirical results (Jacobs & Grainger, 1992; McClelland, 1986; Segui & Grainger, 1990). Note, however, that each basic hypothesis concerning the nature of orthographic codes induces a particular topology for the space of letter strings, and thus, the orthographic similarity can be defined in very different ways depending on the specific basic model. For example, if one considers position-specific letter codes as in the Interactive Activation Model, then two distinct letter strings are maximally similar if they are made of the same letters at the same positions except one (e.g. DEADLINE-HEADLINE), which corresponds to "orthographic neighbors" in the sense of Coltheart, Davelaar, Jonasson, and Besner (1977). In this framework, anagrams cannot be orthographic neighbors, since they differ by at least two orthographic units. However, if one considers position-free letter codes, as in Neocognitrons, two anagrams are in fact made of the same orthographic units, and thus are in some way similar, while the order information must be coded separately.

A variety of studies have addressed the issue of position-specific letter codes (for a review, see Mathey, 2001). One of the most famous observed effects is the so-called "neighborhood frequency effect" (Grainger, O'Regan, Jacobs & Segui, 1989, 1992; Grainger & Segui, 1990; Jacobs & Grainger, 1992). For example, in a lexical decision task, it was observed that the response time to a word with at least one orthographic neighbor (in the sense of Coltheart & al., 1977) of higher frequency of use than itself is longer than the response time to a word with the same frequency of use but lacking a more frequent orthographic neighbor. In an Interactive-Activation framework, neighborhood frequency effects can be interpreted in terms of inhibiting connections between lexical nodes representing orthographic neighbors, with the nodes of the most frequent words being activated more quickly by the input and thereby producing temporary inhibition of the less frequent neighbors. In an Activation-Verification framework, neighborhood frequency effects can be interpreted in terms of the joint activation, by the input, of several orthographic neighbor candidates, which would be checked one by one in decreasing order of frequency of use until the correct candidate is identified.

However, the idea of absolute position-dependent letter codes is incompatible with certain results obtained in perceptual identification and lexical decision experiments with masked orthographic priming (Humphreys, Evett, & Quinlan, 1990; Peressotti & Grainger, 1999). For example, it was observed that the prime BLCN facilitated the recognition of the target French word BALCON as well as the prime B-LC-N, while the prime NLCB did not produce facilitation. Hence, the letter positions must be encoded in a relative way instead of an absolute one. In this case, the orthographic neighborhood, in the sense used above, is only a particular case of orthographic similarity, and one can find more suitable measures of the orthographic similarity such as, for example, the so-called "edition distance" based on a Dynamic Programming approach (Wagner & Fischer, 1974). Recent models of relative letter position coding use "open-bigrams" as coding units (Grainger & van Heuven, 2003; Schoonbaert & Grainger, 2004; Whitney, 2001). Open-bigrams are ordered pairs of adjacent or non-adjacent letters of the string. As an example, in the string CART, the set of open-bigrams is {CA, CR, CT, AR, AT, RT}. These models are based on the principle of "spatial coding" (Grossberg, 1978), where the activation level of a detected letter depends on its position, and this activation level decreases from the left-most positions to the right-most positions, or, more generally, following the writing direction of the considered language, as suggested by recent data (Kwantes & Mewhort, 2002). Then the models transform the relative activation of letters into an activation of open-bigrams (Whitney, 2001). Note that relative position coding models are compatible with the idea of position-free letter codes, but these ones are not assumed to be directly used for lexical access.

There are also some empirical evidences concerned with the idea that position-free letter codes could be used for lexical access. Chambers (1979) observed interference effects between close anagrams (e.g. BALE-ABLE), and these effects were confirmed in lexical decision and naming tasks by Andrews (1996), who proposed an interpretation in terms of approximate coding of letters' position, as also predicted by Ratcliff (1981)'s theory. The similarity of close anagrams can be suitably measured using an extended version of the edition distance (Lowrance & Wagner, 1975). Courrieu (1985), using a lexical decision task with masked orthographic priming and a masked target (40 ms SOA), found that the probability of identifying a target word (that had no lexical anagrams) was modified whenever the prime was a non-word anagram of the target, although the prime and the target never had their common letters at the same position and were not close anagrams. Anagram priming effects depended on the structure of the anagram in a way that suggests a particular role of bigrams in the encoding of order information, while the distance of transposed letters *per se* did not appear relevant. Taking into account a few bigrams is commonly sufficient for solving an anagram. For example, the presence of the bigram 'EA' in the string MEAN excludes its anagrams NAME, MANE, and AMEN. In fact, one knows that certain small multi-letter units (functional spelling units) may play an important role in the phonological encoding of letter strings (Pring, 1981). On the other hand, certain observations of (voluntary) anagram solving processes strongly suggested that the integration of letter strings is linked to their phonological encoding (Fink & Weisberg, 1981), and it seems that phonological encoding can occur quite rapidly (but later than orthographic encoding) in visual word recognition (Ziegler, Ferrand, Jacobs, Rey, & Grainger, 2000). Perea and Lupker (2004) found anagram priming effects, in a lexical decision task, with nonadjacent transposed letters. However these effects were detectable for target words only when the transposed letters were consonants, while transposed vowels did not provide priming for words, and provided only weak priming effects for non-words. Given that the distinction between consonants and vowels is of phonological nature, this suggests a possible role of a phonological coding in the processing of letter order, however other explanations are possible in terms of a modified open-bigram theory.

While most studies focused on the question of how letter order is encoded, there is little data concerning the consequences of a possible use of position-free letter codes (as in Neocognitrons) for lexical access, despite the suggestive fact that 91% of the words do not have lexical anagrams, in French and in English as well (Deloche, Debili, & Andreewsky, 1980), and thus only 9% of the words theoretically require the order information to be taken into account (see also Shillcock, Ellison, & Monaghan, 2000). The present study provides some new data concerning the hypothesis that position-free letter codes are used in lexical access. Note that the hypothesis is not that the order information is not taken into account, but that the letter position, as additional information, is not directly available in letter codes, which are assumed to be translation invariant (and also invariant through some other geometrical transformations, according to Neocognitron models). In this framework, it is clear that the anagram relationship, within the lexicon or between stimuli, constitutes a form of orthographic similarity whose effects on reading performance should be detectable. However, Neocognitrons are pure visual analyzers, they do not use any orthographic constraint, and to date, no lexical stage has been implemented in these models. Hence, specific predictions concerning lexical access can only be derived from the properties of their output neurons, which correspond to translation invariant letter codes. A possible strategy consists of reproducing some well-known orthographic similarity effects, such as the neighborhood frequency effect, while using the anagram relationship as the orthographic similarity factor. One can also attempt to interpret the observed effects in the framework of well-known word recognition models, replacing their position-specific letter codes by position-free letter codes. This is addressed in the following four experiments.

EXPERIMENT 1

The purpose of this experiment was to provide evidence of an "anagram frequency effect" analogous to the well known "neighborhood frequency effect" in a lexical decision task. The potential interpretations of these effects differ only by the position-free nature of the underlying letter codes.

Method

Participants

Twenty-four university students (12 women and 12 men) volunteered to participate in the experiment. Their native language was French, and they all had normal or corrected-to-normal vision.

Material

The stimuli were twenty-eight 5-letter words and twenty-eight, regular 5-letter pseudo-words written in lowercase letters with the necessary French diacritical marks. An additional 12 words and 12 pseudo-words were used for training the participants to the task. The frequency of use of each test word was controlled using the logarithm of the absolute frequency given in the *Trésor de la Langue Française* (T.L.F.) (1971). On this scale, the log-frequencies range from 0, for words which occurred only once in the corpus of 70,317,234 occurrences of the T.L.F., to 12.9 for the most frequent words (e.g. the French preposition "de" (of)). The lexical anagrams of the test words were controlled in reference to the *Larousse du Scrabble* (1978). The number of orthographic neighbors (N-count) of the stimuli was also controlled. The 28 test words were divided into 4 categories of 7 words each. This gave us (1) 7 frequent words, each of which was the most frequent of a set of 3 lexical anagrams, (2) 7 infrequent words each of which was the least frequent of a set of 3 lexical anagrams (the anagrams in these sets were never the same as those in the frequent test word sets), (3) 7 frequent words with no lexical anagrams (other than themselves), and (4) 7 infrequent words with no lexical anagrams (other than themselves). The last two categories were matched in frequency to the first two. The log-frequency and N-count statistics of the material are given in Table 1. An analysis of variance on the N-counts showed no significant differences across conditions (all F's < 1).

Procedure

The stimuli were displayed in the center of a computer screen (50 Hz synchronized, rapid phosphorus cathodic screen). The letters in the stimuli were defined in a fixed 7x7 pixel matrix, and were presented in a light color on a dark background. The stimuli always subtended a visual angle of less than 2 degrees. A trial began with the display of a fixation point. Then a tone rang, and 500 ms later, the stimulus was displayed with the third letter placed at the fixation point. The participant was supposed to decide as quickly and as accurately as possible whether the stimulus was a word in the French language. The lexical decision was entered by pressing a key marked "oui" (yes) or a key marked "non" (no). The participant's responses and response times (in ms) were recorded by the computer. The stimulus disappeared when the answer was given, and the next trial started 3 seconds later. The testing began with 24 practice trials of words and pseudo-words presented in a fixed, random order. These were followed by 56 trials of stimuli presented in random order, randomly varied across participants.

Table 1. Mean log-frequency of use and number of orthographic neighbors (with standard deviation) of the test words used in Experiment 1.

	Anagrams	Non Anagrams
Frequent words		
log-frequency of use	9.04 (0.60)	9.02 (0.63)
N-count	2.29 (1.60)	3.00 (2.77)
Infrequent words		
log-frequency of use	4.96 (0.52)	4.90 (0.69)
N-count	3.00 (0.82)	2.57 (1.81)

Statistical Analysis

Response times (and accuracy data, for control) were input into an analysis of variance without any correction or exclusion, thus the full random variance of data was preserved (this is true for all experiments in this paper). The independent variables were the word's frequency of use (frequent vs. infrequent), and the number of lexical anagrams the stimulus had (anagram vs. non-anagram). The F-ratios for the participant population (F1) and the item population (F2) were computed. In addition, we computed Quasi-F ratios (F' formula), which provide a severe test of effects with respect to the participant and item populations simultaneously. Quasi-F ratio tests are suitable to experimental designs using sampled materials that cannot be counterbalanced (Wickens & Kepple, 1983; Winer, 1971, pp. 357-378). In addition, the use of such a severe test, together with a preserved full random variance, prevents any abusive positive conclusion, particularly in the case of a relatively low experimental power (only 7 items per condition, due to selection constraints).

Results

The mean response times and percentages of correct responses are presented in Table 2. The response times were significantly shorter for the frequent words than for the infrequent ones ($F1(1, 23)=18.25$, $p<.001$; $F2(1, 24)=44.04$, $p<.001$; $F'(1, 28)=15.38$, $p<.001$). No significant main effect of the number of lexical anagrams was observed, but there was a significant interaction between the number of lexical anagrams and the frequency of use ($F1(1, 23)=6.52$, $p<.02$; $F2(1, 24)=5.61$, $p<.03$; $F'(1, 23)=4.28$, $p<.05$). Analysis of the simple effects showed that the number of anagrams did not have a significant effect on the response time to frequent words (all F's < 1), but the infrequent anagrams took more time to recognize than infrequent non-anagrams. This effect was significant for participants and items alike ($F1(1, 69)=4.17$, $p<.05$; F2(1, 24)=5.60, p<.03) and marginally significant for the Quasi-F ratio (F'(1, 47)=3.13, p<.08). The observed significant interaction can thus be explained essentially by this last simple effect, so the obtained result is exactly the expected one, that is, one obtained an anagram frequency effect equivalent to the well known neighborhood frequency effect. The pattern of errors was similar to the pattern of response times, so no speed-accuracy tradeoff must be suspected, and there would be no justification to exclude error response times.

Table 2. Mean response time (ms) and percentage of correct lexical decisions in Experiment 1.

	Anagrams	Non Anagrams	
Frequent	575 (100%)	598 (99%)	587 (99%)
Infrequent	721 (93%)	667 (96%)	694 (95%)
	648 (97%)	632 (98%)	

Discussion

These results indicate an anagram frequency effect analogous to the well-known neighborhood frequency effect. This suggests that the anagram relationship can constitute another form of orthographic similarity, and thus that the orthographic codes used during lexical access cannot be reduced to position-specific letter codes. However, one could object that there is a possible bias connected to the fact that there is a non-negligible correlation between the number of lexical anagrams and the log-frequency of the individual letters in the words. Consequently, we checked the log-frequency of the letters in our experimental material (Table 3). The suspected correlation was confirmed: the log-frequency of anagram letters was significantly greater than that of non-anagram letters ($F(1, 24)=21.86$, $p<.001$).

Table 3. Mean log-frequency (with standard deviation) of individual letters in the test words of Experiment 1.

	Anagrams	Non Anagrams	
Frequent	6.13 (0.17)	5.76 (0.25)	5.95 (0.28)
Infrequent	6.12 (0.13)	5.89 (0.07)	6.00 (0.16)
	6.13 (0.15)	5.83 (0.19)	

As it is difficult in practice to separate the number of lexical anagrams from the frequency of letters, we did an *a posteriori* analysis of the partial correlations between the different explanatory variables and the response time. Remember that partial, three-variable correlations can be used to estimate two-variable correlations, the effect of the third variable being eliminated. The analyses were done separately for the two frequency levels, so that each correlation was computed on a set of 14 words. The variables studied were the response time (T), the number of lexical anagrams (A), which was 1 or 3 in our material, the number of orthographic neighbors (N), and the log-frequency of the individual letters (L). Let r(ij) denote the ordinary correlation between the variables i and j, and let r(ij/k) denote the partial correlation between the variables i and j when the variable k is kept constant. Table 4 presents the results of this analysis. As one can see in Table 4, there was a strong correlation between A and L for both the frequent ($r=0.68$, $df=12$, $p<.01$) and the infrequent words ($r=0.76$, $df=12$, $p<.01$), which simply corresponds to the bias reported above. For infrequent words, one observed a significant positive partial correlation between A and T for L constant (r=0.55, df=11, p<.05), which shows that the anagram frequency effect was independent of the letter frequency effect. Moreover, the partial correlation between L and T for A constant was negative (r= -0.35, n.s.), that is, A and L tended in fact to have opposite effects on the response time. No significant effect of N on T was detected, however this results from the fact that the material of this experiment was not selected in order to allow the detection of neighborhood effects.

Table 4. Correlations between the log-frequency of letters (L), the number of lexical anagrams (A), the number of orthographic neighbors (N), and partial correlations of these variables with the response time (T) in Experiment 1. Note that r(xT/y) denotes the partial correlation between x and T for y constant.

	Frequent words	
r(AL) = 0.68	r(AT/L) = -0.43	r(LT/A) = 0.21
r(NL) = 0.18	r(NT/L) = -0.18	r(LT/N) = -0.11
r(AN) = 0.16	r(AT/N) = -0.39	r(NT/A) = -0.15
	Infrequent words	
r(AL) = 0.76	r(AT/L) = 0.55	r(LT/A) = -0.35
r(NL) = 0.16	r(NT/L) = -0.07	r(LT/N) = 0.17
r(AN) = -0.17	r(AT/N) = 0.48	r(NT/A) = 0.05

EXPERIMENT 2

Suppose, as the results of Experiment 1 suggest, that position-free letter codes are used during lexical access. What happens if, before a test word, we present a prime that is its anagram? In principle, all the lexical anagrams of the prime will be pre-activated, but if we agree with the general hypothesis of the Interactive Activation model, the more frequent candidates will inhibit the less frequent ones. This leads us to predict that an anagram prime will facilitate its more frequent lexical anagrams, whereas it will either facilitate to a lesser degree or inhibit the less frequent lexical anagrams. However, in cases where the prime has only one lexical anagram, it can only be facilitated because it has no inhibiting competitor. Before testing these predictions, we must consider the time course of processes in order to choose suitable SOAs. The overall processing of a letter string, or of a word, typically requires several hundreds milliseconds. So it is not clear that with very short SOAs, a prime will be processed before the target. It seems plausible that, in this case, the processing of the prime and the target will largely overlap, and thus the priming effects depend on the compatibility of the two processes, while our experimental reasoning is in terms of residual pre-activation and pre-inhibition. Thus it is clear that we must choose SOAs that are not too short in order to test the above predictions.

Method

Participants

Twenty-four university students (12 women and 12 men) volunteered to participate in the experiment. Their native language was French, and they all had normal or corrected-to-normal vision.

Procedure

The general characteristics of the experimental device were identical to those in Experiment 1. An experimental trial began with the display of a fixation point in the center of the screen. Then a tone rang, and 500 ms later, a string of 5 letters was displayed with the third letter placed at the fixation point. This stimulus (prime) remained on the screen for 200 ms, and was then masked by a string of 5 asterisks (which also remained on the screen for 200 ms) designed to prevent direct visual "correlations" across stimuli. Finally, the asterisks were replaced by a 5-letter stimulus that was either a word or a regular pseudo-word (target), and remained on the screen until the participant made a lexical decision (on the latter stimulus only) by pressing the yes or no key. The participant's responses and response times (in ms) were recorded. The test stimulus was erased as soon as the response was given, and the next trial began 3 seconds later. The testing began with 24 practice trials in a constant, random order. These were followed by 96 trials in a random order which varied randomly across participants.

Material

Three sets of sixteen, 5-letter test words (lowercase letters, with diacritical marks) were selected to be used as the second stimulus (target). Each set contained 8 frequent words and 8 infrequent words (see the log-frequencies in Table 5). Each word in sets 1 and 2 had between 1 and 3 anagrams (other than itself) in the French lexicon, and the two sets were balanced for the number of anagrams. The words in set 3 had no lexical anagrams. To each test word, one associated an anagram such that the common letters of the two strings never were at the same position. For the set 1, the associated anagram was always a French word, while for sets 2 and 3 its was always a non-word. Each group of 8 words in each set was divided into two sub-groups of four words. In one of two sub-groups, the anagram of the test word was taken as the prime, while in the other sub-group, anagrams were swapped between test words, so that the prime was not anagram of the target. In all cases, the prime and the target never had similar letters at the same position. The sub-groups with and without anagram prime were swapped for half the participants, thus the items (targets and primes as well) were balanced with respect to the anagram-control prime conditions. The distractors were 48 regular 5-letter pseudo-words preceded by a word in 16 cases and a non-word in 32 cases, with the first stimulus being anagram of the second half of the time. An additional set of 24 prime-target pairs was selected for training, with the same characteristics as the rest of the material.

Table 5. Mean log-frequency of use (with standard deviation) of the test words used in Experiment 2.

	Set 1	Set 2	Set 3
	Anagrams	Anagrams	Non Anagrams
Frequent	7.73 (1.40)	7.72 (1.35)	7.72 (1.38)
Infrequent	4.89 (0.36)	4.90 (0.39)	4.88 (0.37)

Results

The mean response times and correct response percentages are presented in Table 6. Given the counterbalanced experimental design, the data were input into two separate analysis of variance, one for participants and one for items. The independent variables were the target frequency of use (frequent vs. infrequent), the type of prime (anagram vs. control), and the set (1, 2, 3).

Concerning the set factor, the opposition of the first set to the other two refers to the lexicality of the prime (word prime vs. non-word prime), whereas the opposition between the first two sets and the last one refers to the number of lexical anagrams of the target (lexical anagrams vs. no anagrams).

For response times, there was a significant effect of the test word's frequency of use ($F1(1, 22)=33.81$, $p<.001$; $F2(1, 42)=14.98$, $p<.001$), and a significant three-way interaction between the frequency of use, the type of prime, and the set ($F1(2, 44)=5.26$, $p<.01$; $F2(2, 42)=3.97$, $p<.03$). To analyze this interaction, the data for frequent and infrequent target words were separated. For the frequent words, there was no significant effect of the type of prime or the set. In contrast, for infrequent words, there was a significant interaction between the type of prime and the set ($F1(2, 44)=4.18$, $p<.02$; F2(2,21=3.69, $p<.04$). A significant partial interaction between the type of prime and the number of lexical anagrams of the target (i.e. (anagram vs. control) x ((set 1, set 2) vs. set 3)) was extracted ($F1(1, 44)=7.85$, $p<.01$; $F2(1, 21)=6.93$, $p<.02$), and the residual effect was non-significant (all F's < 1), i.e. the lexicality of the prime was not a relevant factor. Breaking down the significant partial interaction, one observed a non-significant facilitating effect (59 ms) of the anagram prime when the target word had lexical anagrams ($F1(1, 22)=2.16$; $F2(1, 14)=1.88$), while there was a significant inhibiting effect (122 ms) of the anagram prime when the target word did not have lexical anagrams ($F1(1, 22)=12.68$, $p<.002$; $F2(1, 7)=7.31$, $p<.03$). In addition, an analysis concerning only infrequent words with a control prime showed that infrequent words which had no lexical anagrams (sets 3) were recognized faster (125 ms) than those which had lexical anagrams (sets 1 and 2). This effect, which replicated the one observed in Experiment 1, was significant with respect to the participant population ($F1(1, 44)=5.73$, $p<.02$), and marginally significant with respect to the item population ($F2(1, 21)=3.38$, p<.08). The residual comparison (set 1 vs. set 2) was not significant (all F's < 1). Finally, the errors varied in the same way as the response times.

Table 6. Mean response time (ms) and percentage of correct lexical decisions in Experiment 2.

	Set 1 Anagrams Word prime	Set 2 Anagrams Nonword prime	Set 3 Non Anagrams Nonword prime
Frequent word			
Anagram prime	667 (95%)	649 (99%)	629 (95%)
Control prime	680 (97%)	616 (96%)	639 (100%)
Infrequent word			
Anagram prime	732 (93%)	738 (86%)	792 (82%)
Control prime	765 (93%)	824 (83%)	670 (94%)

Discussion

No significant effect of the anagram factors was observed for frequent target words. In contrast, these factors interacted for infrequent words in such a way that an anagram prime of the test word produced an inhibiting effect when the test word did not have lexical anagrams, while producing a non-significant facilitating effect when the test word did have lexical anagrams. This effect will be referred to as the "anagram-prime x lexical-anagram interaction effect". As in Experiment 1, the results are meaningless if one does not assume that position-free letter codes are used in lexical access. The fact that frequent words appeared insensitive to the anagram factors could suggest that these words parallely benefit by another type of processing, however their impact on the processing of their infrequent lexical anagrams suggests that frequent words are not disconnected from the position-free letter processing system. It remains that the observed anagram-prime x lexical-anagram interaction effect was exactly the opposite of the one predicted by the Interactive-Activation hypothesis. Perhaps we would have better luck with the Activation-Verification hypothesis. On several occasions, effects have been observed suggesting that whenever an entry in the mental lexicon has triggered a false detection, diagnosed by a checking process, the lexical entry in question is temporarily inhibited (see for example Davelaar, Coltheart, Besner, & Jonasson, 1978). If this is true, then in cases where we present an anagram prime before a test word with no lexical anagrams, the unique lexical anagram of the prime (i.e. the test word) is activated, checking ensues, the error is diagnosed, and the lexical entry is inhibited, in such a way that when the corresponding word is actually presented an instant later, its recognition is slower due to residual inhibition. However, if the test word has lexical anagrams which are more frequent than itself, these candidates would also be activated by the prime, and checked first, in such a way that if the SOA is not too long, the entry corresponding to the test word may not get checked before the test word appears. In this case it would be facilitated by anagram preactivation but would not be subject to the inhibition resulting from the checking process. The Activation-Verification hypothesis thus appears to account for the observed results, but if so, the SOA between the prime and the test word must be a critical factor.

EXPERIMENT 3

According to the Activation-Verification hypothesis formulated above, if we take situations similar to the ones used in Experiment 2 and modify the SOA between the prime and the test word, we can make the following predictions. A reduction in SOA should cause a reduction in the probability that candidates activated by the anagram prime will be checked. In this case, the inhibiting effects should disappear, and facilitating effects should appear. In contrast, an increase in SOA should increase the probability that inhibiting checking will take place before the presentation of the test word.

Method

Participants

Thirty-two university students (16 women and 16 men) volunteered to participate in the experiment. Their native language was French, and they all had normal or corrected-to-normal vision.

Procedure

The procedure was the same as in Experiment 2, except that two SOAs were used, one shorter and one longer than in Experiment 2. With the short SOA, both the prime and the mask were displayed for 100 ms each. With the long SOA, both were displayed for 400 ms each. Each participant was tested under both SOA conditions, in succession, with the order of conditions reversed for half of the participants. Twenty-four practice trials preceded each condition.

Material

Two lists of sixteen, infrequent 5-letter words were selected, with the frequencies of use balanced across lists. The words in the first list all had lexical anagrams more frequent than themselves, while the words in the second list did not have lexical anagrams. For each word, a non-lexical anagram with no common letters at the same position was generated. This served as the anagram prime for the test word in one condition, and as the control prime for another word in another condition. The prime-target pairing was counterbalanced in the same manner as in Experiment 2. In all cases, the prime and the test word had no common letters in the same position. The assignment of the stimuli to the SOA conditions was also counterbalanced. The set of stimuli was completed with an equal number of distractors, which were regular, 5-letter pseudo-words equiprobably paired with an anagram or non-anagram prime.

Results

The mean response times and percentages of correct lexical decisions are given in Table 7. A significant overall interaction was found between the type of prime and the number of lexical anagrams of the test word ($F1(1, 24)=6.49$, $p<.03$; $F2(1, 30)=5.42$, $p<.03$).This interaction is a replication of the anagram-prime x lexical anagram interaction effect found in Experiment 2 for infrequent words, and it did not depend significantly on the SOA. For the words with lexical anagrams, there was a non-significant interaction between the type of prime and the SOA ($F1(1, 24)=3.99$, $p<.06$; $F2(1, 15)=1.55$). The anagram prime had no detectable effect at the short SOA, and produced a non-significant facilitation effect (69 ms) with the long SOA. Note that these possible effects are in fact opposite to the expected ones. For words with no lexical anagrams, the effect of the anagram prime did not depend significantly on the SOA. There was an overall inhibition effect (74 ms), significant for the participant analysis ($F1(1, 24)=7.03$, $p<.02$), and marginally significant for the item analysis ($F2(1, 15)=3.27$, $p<.09$).

Table 7. Mean response time (ms) and percentage of correct lexical decisions in Experiment 3.

	Anagram word	Non anagram word
Short SOA		
Anagram prime	809 (94%)	857 (94%)
Control prime	807 (94%)	794 (95%)
Long SOA		
Anagram prime	756 (96%)	860 (94%)
Control prime	825 (94%)	776 (96%)

Discussion

The SOA effects predicted by the Activation-Verification hypothesis were not obtained, while the anagram-prime x lexical anagram interaction effect observed in Experiment 2 was replicated in Experiment 3, and it appeared to be independent of the SOA. We are thus dealing with quite robust anagram effects, consistent with the use of position-free letter codes in lexical access. Neither the Activation-Verification model nor the Interactive Activation model is able to predict the observed results, even when the assumed nature of the letter codes is modified.

EXPERIMENT 4

In Experiments 2 and 3, we observed non-significant tendencies for an anagram prime to facilitate the recognition of infrequent words possessing lexical anagrams. These tendencies were observed only at the longest SOAs. However, we suspected that this was not linked to the SOA *per se*, since facilitating anagram priming effects have previously been observed with a masked priming technique at a SOA of only 40 ms (Courrieu, 1985, Exp. 2). On the other hand, in the present Experiments 2 and 3, a number of participants said that the prime was a hindrance and that they attempted to ignore it. In Experiment 4 we ask: what happens whenever an anagram prime is fully processed? This can be obtained if the participants must provide a response on the prime as well as on the target.

Method

Participants

Thirty-two university students (16 women and 16 men) volunteered to participate in the experiment. Their native language was French, and they all had normal or corrected-to-normal vision.

Material

The stimuli were all 5 characters long and written in lowercase letters with the necessary diacritical marks. We selected 10 pairs of words that were anagrams of each other but had no common letters in the same position. In each pair, one of the two words was always much more frequent than the other. The log-frequency means (and standard deviations) were 8.59 (1.35) and 5.15 (1.16), respectively. In half of the anagram pairs, the more frequent word occurred first, and in the other half, the less frequent word came first. The ordering of the pairs was reversed for half of the participants, in such a way that for the experiment as a whole, each item occurred the same number of times in first or second position. This material was completed with 15 anagram pairs, from which 5 pairs pseudo-word+word, 5 pairs word+pseudo-word, 5 pairs pseudo-word+pseudo-word. The pseudo-words were regular, and the words were sampled over a large range of frequencies. In addition, 24 non-anagram practice pairs were included.

Procedure

A self-presentation procedure was used in this experiment. An experimental trial started with the display of a string of 5 asterisks in the center of the computer screen. Then a tone rang to announce that the trial could begin. The participant was supposed to display the first stimulus by pressing the yes key. This caused the first stimulus to replace the asterisks, then the participant was supposed to quickly strike the yes or no key to state whether or not the stimulus was a word in the French language. As soon as this lexical decision was entered, the stimulus was replaced by a new string of 5 asterisks, and the participant displayed the second stimulus by pressing the yes key. Then a new lexical decision was entered as quickly as possible, the stimulus disappeared, and the next trial began 3 seconds later. The participant's responses and response times (in ms) were recorded. The 24 practice trial pairs were presented in a constant, random order, followed by 25 pairs in a random order that varied randomly across participants.

Results

Since the experimental design was counterbalanced, separate analysis of variance for participants and items were performed. These analysis concerned the word+word anagram pairs. The independent variables were the relative frequency of use of the word (more frequent, less frequent) and its rank in the display sequence (first, second). The first rank was the control, and the second rank was the "primed" rank.

The mean response times and percentages of correct lexical decisions are given in Table 8. For the response times, the main effect of the frequency of use was significant ($F1(1, 30)=48.66$, $p<.001$; $F2(1, 18)= 18.59$, $p<.001$), the main effect of the rank was non-significant, and there was a marginally significant interaction between the frequency of use and the rank ($F1(1, 30)=3.11$, $p<.09$; $F2(1, 18)=3.88$, $p<.07$). Analysis of simple effects showed that the prior presentation of the less frequent anagram had no significant effect on the recognition time of the more frequent anagram (all F's < 1), whereas the prior presentation of the more frequent anagram had a significant, facilitating effect (65 ms) on the recognition of the less frequent anagram ($F1(1, 90)=6.35$, $p<.02$; $F2(1, 9)=6.62$, $p<.03$).

Discussion

This final result showed that the presentation of a frequent word had a facilitatory effect on the subsequent recognition of its less frequent lexical anagram, even though the two words had no common letters in the same position. Note that this positive effect, which occurred when the frequent anagram was in fact presented, is the opposite of the negative effect observed in Experiment 1, where the more frequent anagram was not presented. We note also that the prior presentation of the less frequent anagram had no detectable effect on the subsequent recognition of the more frequent one. Given that the prime was fully processed in this experiment, one could suspect that some kind of anagram relationship based predicting strategy was used by the participants. However, given that frequent words are *a priori* more predictable than infrequent words, a predicting strategy should have produced facilitatory effects on frequent anagrams at least as well as on infrequent anagrams, which does not match the observed pattern of results. Thus, a plausible interpretation is that frequent anagrams provide activation to their less frequent anagrams (anagram priming effect), while the opposite is not true. As we shall see below, this hypothesis also allows for understanding the anagram prime x lexical anagram interaction effect observed in Experiments 2 and 3, as well as (paradoxically) the anagram frequency effect observed in Experiment 1.

Table 8. Mean response time (ms) and percentage of correct lexical decisions in Experiment 4.

	Most frequent anagram	Less frequent anagram
First	763 (99%)	918 (94%)
Second	773 (99%)	853 (96%)

General Discussion

We found, in Experiment 1, an "anagram frequency effect" equivalent to the well known "neighborhood frequency effect" (Grainger, O'Regan, Jacobs & Segui, 1989, 1992; Grainger & Segui, 1990; Jacobs & Grainger, 1992), that is, an infrequent word that has at least one frequent anagram was longer to recognize than a word of the same frequency of use that has no lexical anagram. This indicates that the anagram relationship is a kind of orthographic similarity, and thus, the concept of position-free letter codes is relevant in the context of the word recognition. We found, in Experiment 2, an "anagram prime x lexical anagram interaction effect" on infrequent target words, while frequent words appeared insensitive to the anagram priming. The structure of the observed interaction was inconsistent with the Interactive-Activation hypothesis, while the Activation-Verification hypothesis provided a possible interpretative framework, and predicted an interaction with the SOA. This prediction was tested in Experiment 3, where the anagram prime x lexical anagram interaction observed in Experiment 2 was replicated and appeared independent of the SOA. Hence the Activation-Verification hypothesis failed to explain the results. The structure of the anagram prime x lexical anagram interaction observed in Experiments 2 and 3 was such that an infrequent word that had no lexical anagram was strongly inhibited by an anagram prime, while an infrequent word that had at least one more frequent anagram in the lexicon was not inhibited by an anagram prime, and we even observed a non-significant facilitatory effect of the anagram prime at the longest SOAs. In Experiment 4, we used a procedure that implies full processing of the prime, and we observed that the prior presentation of a frequent anagram word significantly facilitated the subsequent recognition of one of its less frequent lexical anagrams, while the prior presentation of an infrequent anagram did not influenced the subsequent recognition of its more frequent anagram. To provide a coherent interpretative framework to all these results, we consider first the inhibitory effect of an anagram prime on words that have no lexical anagrams (Exp. 2 and 3). This effect shows two things. Firstly, of course, two anagram strings are not perceptually independent, even though they have no common letters at the same position. Secondly, order information, whenever it is different in the prime and the target, has a strong inhibitory effect. These conclusions are similar to those drawn from previous results (Courrieu, 1985). However, why does the inhibitory effect of the anagram prime vanish whenever the target word has a frequent lexical anagram? We sketch here the outline of a possible model.

Assume that each time that a new word is learned, within the mental lexicon, the following occurs. If the new word does not look like any other known word, then the new word receives a complete description, that is, its node receives all appropriate connections from lower level processing units. If the new word looks like some previously learned words (say its "big brothers"), then the nodes corresponding to these words are partially activated by the new stimulus. Hence, instead of receiving a full description, the new processing unit receives activating input connections from its big brothers' nodes, and only a few additional input from lower level processes, in order to encode its difference from its big brothers. This is an economical way of connecting a network since it allows for reusing previously learned information, while encoding only the new information (and thus the total number of connections tends to be minimal). In addition, we must make some minimal assumptions concerning the input of lexical nodes. In account of the well-known word frequency effect, we assume that the activating input connections of frequent words are more strongly weighted than those of infrequent words. We assume that lexical nodes can receive connections from simple units such as position-free letter nodes, as well as from more complex units, such as open-bigrams or phonological codes, or any other units that encode the order information. According to the hierarchical complexity organization principle of Neocognitron type models, we assume that small units such as position-free letters are available sooner, in the perceptual analysis of a stimulus, than more complex units (bigrams, phonological codes). We note, however, that the hypothesis of multi-letter units can as well be replaced by another way of encoding the order information, provided that the letter codes themselves remain position-free, and available sooner than order information. Now, how can we understand the observed effects in such a theoretical framework? Given that frequent words have many chances to be learned before infrequent words, the big brothers are in general the most frequent words. If an infrequent word has at least one big brother, then it receives a large part of its activation from the stimulus by the intermediate of the big brother nodes, while if it does not have big brothers then it is directly activated by the perceptual analysis of the stimulus. The delay introduced by the big brother node mediation can explain the "anagram frequency effect" (Exp. 1), as well as the well known "neighborhood frequency effect". Now assume that a prime that is anagram of two words is presented. The most frequent anagram word is activated by position-free letter nodes, and then it provides activation to the less frequent anagram, while the order information directly provides a reduced amount of inhibition to the less frequent anagram node given that this one is poorly connected to the perceptual analyzers. Depending on the relative amount of activation and inhibition it received, the less frequent anagram node can be in various states when the corresponding word is actually presented. The situation is different for an infrequent word that does not have big brothers because its node is richly connected to the perceptual analyzers. Thus when the anagram prime is presented, the node receives some activation from position-free letter nodes, and then it receives a full inhibition from order information processing units (such as open-bigram nodes, phonological nodes, etc.). This could explain the anagram prime x lexical anagram interaction effect observed in Experiments 2 and 3. The fact that frequent words are not sensitive to anagram priming (Exp. 2) could simply mean that their activating input approximately counterbalances their inhibitory input, while infrequent words without a big brother are more sensitive to inhibitory information since, as a result of their low frequency of use, their activating connections are weakly weighted. Finally, when a big brother is fully activated, it provides a large amount of activation to its less frequent anagrams, which explains the anagram priming effect observed in Experiment 4. As one can see, the proposed framework allows for a coherent interpretation of the results, which of course does not mean that this is necessarily the truth. However, it seems that a firm conclusion can be drawn concerning the role of position-free letter codes, since robust effects were observed that do not make sense without this hypothesis.

Conclusion

The anagram relationship was shown to be a strong orthographic similarity factor for human readers, and this similarity produced robust effects on word recognition performance, even though the anagrams did not have any of their common letters at the same position. This implies that position-free letter codes are used for accessing the mental lexicon, while the letter order information is also taken into account, but in a separate way. These findings have theoretical as well as methodological implications. In particular, it seems desirable to build a suitable orthographic similarity measure in order to reliably control the confusability of experimental materials.

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APPENDIX

The test stimuli used in the four experiments are listed below. The frequencies of use can be found in *Trésor de la Langue Française* (1971), while the anagram sets can be found in *Larousse du Scrabble* (1978).

Experiment 1

Frequent anagrams: poser, sacré, lampe, santé, perdu, cause, voile.

Infrequent anagrams: opter, rouet, rebut, piler, urine, store, piton.

Frequent non anagrams: juger, digne, choix, nuage, moral, forme, jouir.

Infrequent non anagrams: miner, canif, cible, cuver, magot, bocal, purge.

Experiment 2.

The pairs (prime-test word) are presented in anagram pairing.

Set 1, frequent test:

acier-craie, sceau-cause, sueur-usure, aimer-maire,

crédo-décor, trois-sorti, repos-prose, merci-crime.

Set 1, infrequent test:

ouest-soute, brute-rebut, extra-taxer, éclat-lacté,

tiers-strie, duper-prude, renom-norme, écran-nacré.

Set 2, frequent test:

eivol-olive, eurot-route, débro-brodé, udegi-guide,

ilega-aigle, henic-chien, ontla-talon, verba-brave.

Set 2, infrequent test:

eusag-sauge, perto-opter, edvir-verdi, ribun-bruni,

emrat-mater, esbra-baser, nemai-manie, ipnot-potin.

Set 3, frequent test:

upero-proue, ymeno-moyen, olbia-aboli, ohrec-roche,

ordul-lourd, disam-admis, adtéb-débat, sipod-poids.

Set 3, infrequent test:

egliu-ligue, icfan-canif, odunt-tondu, hocta-cahot,

tesag-stage, xepru-preux, imunt-mutin, trifé-rétif.

Experiment 3. The pairs (prime-test word) are presented in anagram pairing.

Anagram test word:

renui-urine, retos-store, depur-prude, recai-carie,

levoi-olive, estou-soute, perto-opter, gesau-sauge,

terou-rouet, lerpi-piler, créan-nacré, bretu-rebut,

riset-strie, cléat-lacté, nopit-piton, neuje-enjeu.

Non anagram test word:

ouper-proue, sicol-colis, guiel-ligue, bnaca-caban,

kepro-poker, vecru-cuver, toigg-gigot, tocks-stock,

toclu-culot, roves-verso, thoca-cahot, itang-gitan,

péfri-fripé, nifac-canif, emrim-mimer, expru-preux.

Experiment 4. Anagram pairs are presented with the most frequent first.

éclat-lacté, ouest-soute, porte-opter, sueur-usure, brute-rebut, repos-prose, tiers-strie, jeune-enjeu, perdu-duper, acier-carie.